



Low Density Syntactic Foam Composites as Ablative TPS Material for High Heat Flux Conditions for Reentry Missions

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Abstract

Low density ablative syntactic foam composites based on chopped fiber reinforcement and glass microballoon dispersed in high char-yielding thermoset resin viz, Resole Phenolic Resin (RPR) were investigated as potential thermal protection system for Crew module forward heat shield TPS at high heat flux conditions corresponding orbital re-entry conditions. The composites were prepared by impregnating two type of fibers (Silica and Carbon fiber) with RPR and subsequent curing through compression molding technique. The density of the composites varied from a minimum of 0.48 g/cc to a maximum of 1.1 g/cc achieved by varying the proportions of the individual components. All the varieties of composites showed good mechanical properties (Compressive strength 20–60 MPa) and low thermal conductivity (0.2–0.35 W/mK). Aerothermal properties were evaluated through Kinetic Heat Simulation (KHS) and the tests were carried out for a duration of 1200 s, though the heating history ends at 463 s. Surface degradation was observed in all cases which is progressively improved with increasing density in the case of silica fiber-reinforced composites, whereas the surface degradation pattern was found minimal for the carbon fiber reinforced counterparts. Varying the length of the reinforcement was found to be effective in retaining the integrity of the rest of the bulk material after KHS test. Studies by plasma arc jet test at a heat flux of 120–130 W/cm² for a duration of 20 s resulted in a heat of ablation of 23–25 MJ/kg for the composites. The studies show that ablative systems based on these syntactic foams can be a better candidate as TPS with good mechanical properties and thermal performance with reduced density.

Keywords Ablatives · Syntactic foam composite · Silica fiber · Carbon fiber · KHS test

Introduction

Space flight, including reentry into Earth's atmosphere, entry into planetary atmospheres, and hypersonic flight all require the use at high temperatures and in severe environments for the protection of both vehicles and crews. Thermal Protection System (TPS) materials play a fundamental role for the entire aerospace industry (Hurwicz et al. 1965). Over past 50 years, due to the very large spectrum of hyper-thermal environments in which TPS materials operated, and

depending on the application, many types of heat shielding solutions have been identified and developed for the hyper-thermal environment in which these materials must work (Emde 1995). Ablative materials work by absorbing a great amount of heat through a phase change. A subset of ablators called charring ablators form a char layer which acts as an insulator while the virgin material underneath continues to decompose and outgas (Fig. 1). In terms of reinforcements, especially for small ablatively cooled rocket engines (below 100 kN of thrust), research also evidenced that randomly oriented short reinforcements in form of chopped fabric exhibited good performance both in terms of erosion resistance and of mechanical properties (Natali et al. 2016). In this case, the chopped reinforcements cut from an uncured pre-impregnated fabric (as an example, in the shape of small squares with a dimension of one-half by one-half inch) are compacted by means of compression molding techniques and then cured (Warga 1970); the same approach is used when the ablative is based on chopped fibers.

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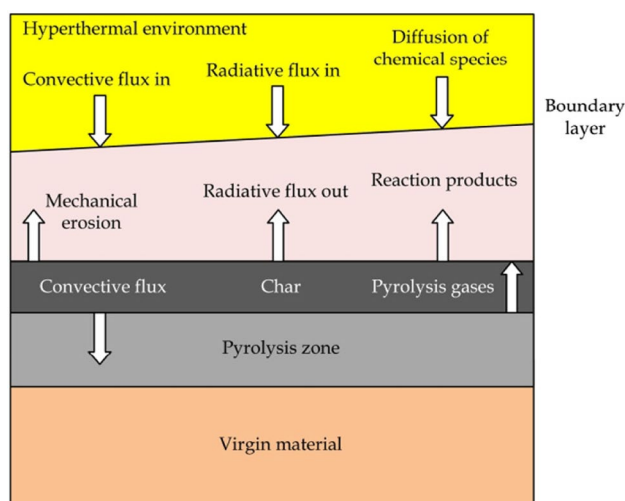


Fig. 1 Ablation processes for charring polymeric ablatives

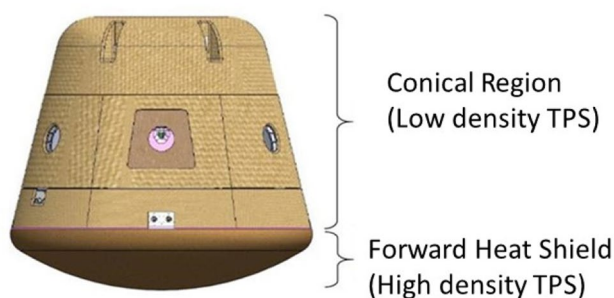


Fig. 2 Schematic of the TPS for typical re-entry Crew Module

Lower density versions of the composite thermal protections system (TPS) is capable of withstanding certain structural loads (mainly shear and compression). Generally, the conical region including apex cover of Crew Module in re-entry missions is protected by the low density TPS variants and these should satisfy the basic requirements of thermal insulation and maintain the mass balance. However, at the forward heat shield region, generally protected by high-density variants such as Carbon-phenolic or Silica Phenolic TPS (Fig. 2). The disadvantage of these systems are their high density and related mass penalty. In this context, it is desirable that a new low-density TPS with sufficient TPS performance is developed to attain huge mass advantage for such applications. Towards this, in this paper, low-density ablative syntactic foam composites based on chopped fiber reinforcement and glass microballoon dispersed in high char-yielding thermoset resin viz, RPR was investigated as potential thermal protection system for Crew module forward heat shield TPS at high heat flux conditions corresponding orbital re-entry conditions.

Experimental

Materials

Resole Phenolic Resin, (RPR), viscosity 300–400 cps at 30 °C, cps was synthesized in house. The microballoon fillers of density 0.37 g/cc (MB-1) and 0.25 g/cc (MB-2) were procured from 3M Company, USA and used as received. Chopped silica fiber having varying length (6 to 12 mm) was supplied by M/s Valent High tech composites Chennai. Carbon fiber T-300 grade was chopped (6–12 mm) and used.

Processing of RPR-Chopped Fiber–Syntactic Foam Compositions

Generally, the syntactic foams are processed by incorporating microballoons into the polymer matrix. Processing of syntactic foam composition was done by the impregnation of glass microspheres, fiber reinforcement (both chopped silica and chopped carbon fiber having varying length of 6–12 mm) using the resin solution in a suitable container. A low concentration of solvent preferably between 15 and 25% by weight with respect to the oligomer was used to control viscosity of the resin. The solvent is then removed by evaporation in an air oven followed by vacuum drying. The syntactic foam composition after complete drying was laid up uniformly in a mold having required dimension. Molding was done in a hydraulic/pneumatic press with a final cure temperature of 180 °C. The cured blocks were cut into desired dimensions for evaluation of physico-chemical and thermo-mechanical properties. In this study about five variants each of chopped silica fiber-reinforced composites (RISA; RISA-1 (0.50 ± 0.02 g/cc) RISA-2 (0.6 ± 0.02 g/cc) RISA (0.7 ± 0.02 g/cc) RISA-4 (0.8 ± 0.02 g/cc) and RISA-5 (1.1 ± 0.02 g/cc)) and carbon fiber-reinforced variants (RICA; RICA-1 (0.50 ± 0.02 g/cc) RICA-2 (0.6 ± 0.02 g/cc) RICA (0.7 ± 0.02 g/cc) RICA-4 (0.8 ± 0.02 g/cc) and RICA-5 (1.1 ± 0.02 g/cc)) having variable densities have been fabricated and evaluated.

Results and Discussion

Mechanical/Physical Properties of Filled Systems-Effect of Density

The density of the composites varied from a minimum of 0.48 g/cc to a maximum of 1.1 g/cc is achieved by varying the proportions of the individual components. For achieving higher densities, the fiber fraction which is having higher density than the low denser microballoon filler in the total

composite volume composition is increased and lower densities is achieved by increasing the filler (glass microballoon) fraction compared to the denser fiber fraction. Mechanical properties of the compositions have been evaluated extensively. As expected, it was noted that the composites show increased strength with increase in density and the compressive strength is varied in the range of 8–17 MPa to 80–90 MPa for Silica fiber variants (RISA) and the carbon fiber reinforced variants (RICA) showed a strength of 30–48 MPa to 80–100 MPa (Table 1).

Thermal Properties

The thermal properties of the prepared composites have been evaluated. It was noted that the thermal properties of the composites such as thermal conductivity and coefficient of thermal expansion (CTE) is highly dependent on the type of reinforcement. For instance, the thermal conductivity of the Silica fiber reinforced composite is found to be lower than carbon fiber reinforced composites (Table 2).

Performance Evaluation of the Samples as Ablators

Kinetic Heat Simulation (KHS) Studies

Aerothermal properties were evaluated through Kinetic Heat Simulation (KHS) and the tests were carried out at 54.4 W/cm² for a duration of 1200 s, though the heating history ends at 463-sec rest was to capture the soak back temperature. Surface degradation observed in all cases which is progressively improved with increasing density in the case of silica fiber reinforced composites, whereas the surface degradation pattern was found minimal for the carbon fiber reinforced counterparts. Varying the length of the reinforcement was found to be effective in retaining the integrity of the rest of the bulk material after KHS test. Typical samples (dimension 150 × 150 × 21 mm) from both carbon fiber reinforced composite and Silica fiber reinforced composites are shown in Fig. 3a,b.

Plasma Arc Jet Evaluations

Through the plasma arc jet test series, the erosion rate, mass loss rate and thermal response of the TPS materials in 6 MW Plasma Wind Tunnel Facility under simulated earth re-entry environment was evaluated (Fig. 4).

The peak heat flux on the fore-body heat shield was considered as 117 W/cm², occurring near the corner.

Subsequent to the calibration run, material tests were conducted in two stages. In Stage-1, test models were exposed for a short duration (20 s) to the calibrated heat flux (125 W/cm² (± 5 W/cm²)) to have a preliminary assessment of the erosion, mass loss and thermal response characteristics. The

Table 1 Compressive properties of the composites

Property	RISA-1	RISA-2	RISA-3	RISA-4	RISA-5	RICA-1	RICA-2	RICA-3	RICA-4	RICA-5
Density (g/cc)	0.50 ± 0.02	0.6 ± 0.02	0.7 ± 0.02	0.8 ± 0.02	1.1 ± 0.02	0.50 ± 0.02	0.6 ± 0.02	0.7 ± 0.02	0.8 ± 0.02	1.1 ± 0.02
Compressive strength (MPa)	8–15	23–31	20–35	50–70	80–90	10–15	30–48	30–40	30–50	80–100
Comp. Modulus (MPa)	900–1000	1200–1800	1500–2300	2900–3100	3300–3500	800–1000	1200–1500	1800–2000	2500–2800	3000–3500

Table 2 Thermal properties of the composites

Property	RISA-1	RISA-2	RISA-3	RISA-4	RISA5	RICA-1	RICA-2	RICA-3	RICA-4	RICA-5
CTE (50–150 °C)/°C (10^{-5})	1.5	2.9	1.7	1.5	2.2	3.3	4.3	4.2	6.6	7.2
Specific heat at 80 °C (cal/g/°C)	0.24	0.24	0.24	0.24	0.25	0.24	0.26	0.23	0.29	0.3
Thermal conductivity at 80 °C W/mK	0.10	0.13	0.16	0.22	0.24	0.19	0.21	0.24	0.27	0.35

Fig. 3 **a** Typical RICA sample before and after KHS test. **b** Typical RISA sample before and after KHS test



(a): Typical RICA sample before and after KHS test



Fig. 4 Photograph of the Arc-Jet long duration test in progress and a typical stagnation test model

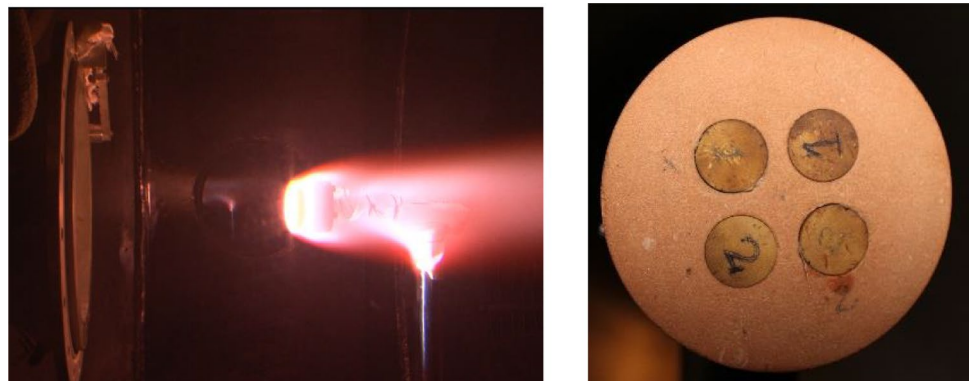
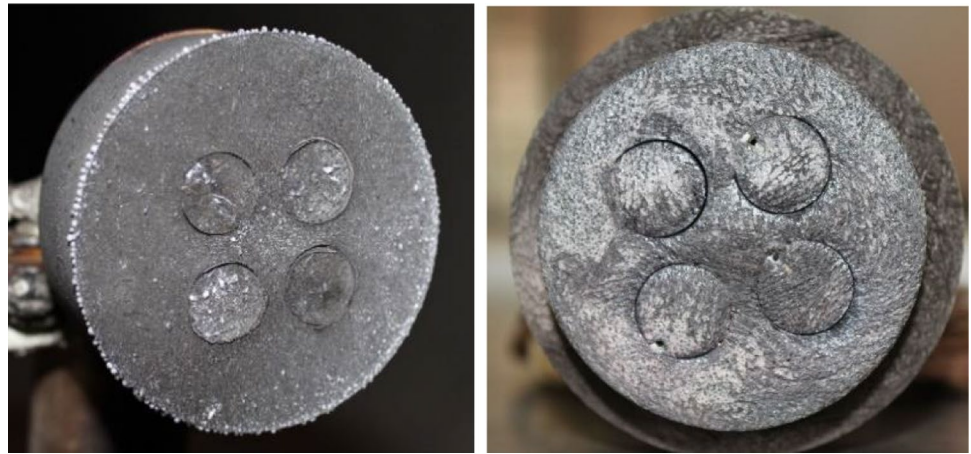


Fig. 5 Post-test photographs of the model (RISA) after short duration and long duration



data thus generated were used to fine tune the requirements of long duration tests. During the short-duration tests, the erosion rate of the compositions is very low. Studies by plasma arc jet test at a heat flux of 120–130 W/cm² for a duration of 20 s resulted in a heat of ablation of 23–25 MJ/kg for the composites. Subsequent to the short-duration tests, tests were conducted for 180 s at heat flux of 125 W/cm² which corresponds to an integral heat load of 22.5 kJ/cm². The post-test photographs of the model (RISA) after short duration and long duration are shown in Fig. 5. The performance parameters evaluated for the TPS materials viz. the erosion rate, mass loss rate (percentage of mass loss from initial mass of the specimen) and temperature response are summarized in Table 3.

module forward heat shield TPS at high heat flux conditions corresponding to the orbital re-entry conditions. The specimens were extensively characterized for their thermal, mechanical and ablative performance. The studies show that ablative systems based on these syntactic foams can be a better candidate as TPS with good mechanical properties and thermal performance with reduced density. Based on the test data available among the set of test specimens, the performance of RISA systems is found to be better than their RICA counterparts.

Conclusions

Low density ablative syntactic foam composites based on chopped fiber reinforcement and glass microballoon dispersed in high char-yielding thermoset resin viz, RPR was investigated as potential thermal protection system for Crew

Table 3 Summary of long duration tests (180 s)

S. no	Material ID	Density (g/cc)	Test duration (s)	Erosion rate (mm/s)	Mass loss rate (g/s-m ²)	Temperature (average) (°C)	Location of sensor from front face (mm)	Mass loss rate (Δm/mi) (%)
1	RISA 4	0.80	180	0.0345	38.40	1250 @ 110 s	6	44.60
2	RISA 2	0.60	180	0.0379	37.78	1250 @ 76 s	6	55.06
3	RICA4	0.80	180	0.0421	52.99	1250 @ 87 s	6	59.02

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